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The Lost Tribes of Charmonium

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To illustrate the campaign to extend our knowledge of the charmonium spectrum, I focus on a puzzling new state, $X(3872) \to \pi^+\pi^- J/\psi$. Studying the influence of open-charm channels on charmonium properties leads us to propose a new charmonium spectroscopy: additional discrete charmonium levels that can be discovered as narrow resonances of charmed and anticharmed mesons. I call attention to open issues for theory and experiment.

1. MISSING LEVELS

New experimental results—including the discoveries of new states—have revitalized the study of heavy quarkonium [1,2,3] and stimulated a fresh wave of theoretical analysis. In this talk, I want to focus on three groups of elusive narrow charmonium states. (1) All interpretations of the charmonium spectrum anticipate two additional $c\bar{c}$ states below $D\bar{D}$ threshold: the $1^1\mathrm{P}_1$ $J^{PC} = 1^{+-}$ level, h_c, near the $1^3\mathrm{P}_J$ centroid, and the $2^1\mathrm{S}_0$ $J^{PC} = 0^{-+}$ level, η_c', the hyperfine partner of $\psi'(3686)$. (2) We have long expected that two unnatural parity states—the $1^1\mathrm{D}_2$ $J^{PC} = 2^{-+}$ level, η_{c2}, and the $1^3\mathrm{D}_2$ $J^{PC} = 2^{--}$ level, ψ_2—would lie between the $D\bar{D}$ and $D\bar{D}^*$ thresholds. Forbidden by parity invariance to decay into two pseudoscalars, these states should be narrow in the traditional charmonium sense. (3) New coupled-channel calculations indicate that several levels with open charm-anticharm decay channels should be observable as narrow structures.

There is still much to be learned from the study of $c\bar{c}$ states. Including the interthreshold region between $2M(D)$ and $M(D) + M(D^*)$, we expect about ten or eleven narrow levels, of which at least seven are already known. Including higher states within 800 MeV of charm threshold, we expect perhaps sixty states, to be observed either as discrete levels or through their collective effect on the total cross section for $e^+e^- \to$ hadrons. A portion of the charmonium spectrum is shown in Figure 1. Nonrelativistic potential models historically have given a good account of the spectrum, but they cannot be the whole story. They are truncated, single-channel treatments that do not contain the full richness of quantum chromodynamics. We are coming closer to a complete theoretical treatment: lattice QCD is increasingly capable for quarkonium spectroscopy—and improvements are coming swiftly [4,5]. On the

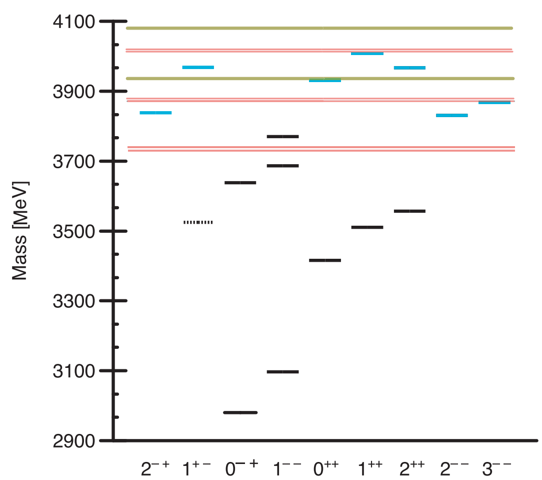

Figure 1. Grotrian diagram for the charmonium spectrum. States marked by heavy black lines are well established. The $^1\mathrm{P}_1$ h_c level is indicated by the dashed line at the $^3\mathrm{P}_J$ centroid. Thresholds are shown, in order of increasing mass, for $D^0\bar{D}^0$, D^+D^-, $D^0\bar{D}^{*0}$, $D^+\bar{D}^{*-}$, $D_s\bar{D}_s$, $D^{*0}\bar{D}^{*0}$, $D^{*+}\bar{D}^{*-}$, and $D_s\bar{D}_s^*$. Some predicted states above threshold are depicted as faint lines.

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experimental side, charmonium states are being seen in electron-positron annihilations, in B decay, in two-photon collisions, and in hadronic production. This circumstance gives us access to a very broad variety of quantum numbers J^{PC}, and makes for a lively conversation among experiments and a fruitful dialogue between theory and experiment.

1.1. Indications for h_c

Twelve years ago, Fermilab experiment E760 reported evidence for resonant formation of the $1^1\mathrm{P}_1$ state of charmonium in proton-antiproton annihilations [6]. They saw a narrow resonance at 3526.2 MeV in the isospin-violating $\pi^0 J/\psi$ channel. The absence of fresh news has left the h_c in limbo.

At this meeting, Claudia Patrignani presented interesting new results from the successor experiment, E835 [7]. In their new data set, they find no evidence for $h_c \to \pi^0 J/\psi$, and infer an upper limit on the product of branching fractions, $\mathcal{B}(h_c \to \bar{p}p)\mathcal{B}(h_c \to \pi^0 J/\psi)$, that is about one-third of the E760 level. However, in the three-photon channel, a preliminary analysis finds 13 $\eta_c\gamma$ candidates close to the $1^3\mathrm{P}_J$ centroid, with an expected background of 1 or 2. Interpreted as examples of $h_c \to \eta_c\gamma$, these events would imply a resonance mass of 3525.8 MeV, with a reasonable value of $\Gamma(h_c \to \bar{p}p)\mathcal{B}(h_c \to \eta_c\gamma)$.

This new E835 work—in the canonical $\gamma\eta_c$ mode—should give added stimulus to the search for the $^1\mathrm{P}_1$ state in other experiments. The cascade decay $B \to h_c K^{(*)} \to \gamma\eta_c K^{(*)}$ offers one promising approach [8,9,10]. In hadron colliders, it may be possible to observe $\eta_c \to \varphi\varphi$ (≈ 3 per mille branching fraction) or another hadronic mode, with or without a secondary vertex tag to enhance B-decay as a source, then to look for the 500-MeV photon from $h_c \to \gamma\eta_c$.[1]

1.2. Discovery of η_c'

Twenty years passed without a confirmation of the Crystal Ball claim of the $2^1\mathrm{S}_0$ $\eta_c'(3594 \pm 5)$ [12], and the complementary technique of charmonium formation in $p\bar{p}$ annihilations did not support the $\eta_c'(3594)$ evidence [13]. In 2002 came Belle's observation of η_c', at a higher mass, in exclusive $B \to KK_SK^{\mp}\pi^{\pm}$ decays [14]. CLEO [15], BaBar [16], and Belle [17] have confirmed and refined the discovery of η_c' in $\gamma\gamma$ collisions, fixing its mass and width as $M(\eta_c') = 3637.7 \pm 4.4$ MeV and $\Gamma(\eta_c') = 19 \pm 10$ MeV [1]. It is worth noting that the 2004 Review of Particle Physics [18] regards the η_c' as needing confirmation. Let us hope for definitive experimental results soon!

The outstanding issue for the $^1\mathrm{S}_0$ $\eta_c'(3638)$ is the small splitting from its $^3\mathrm{S}_1$ hyperfine partner ψ', compared to potential-model expectations, which we shall examine presently.

1.3. Discovery of $X(3872)$

Last summer, Belle [19] discovered $X(3872) \to \pi^+\pi^- J/\psi$, a candidate—by virtue of its decay mode—for a new charmonium state. The observation was confirmed in short order by CDF [20], DØ [21], and BaBar [22]. I summarize the observations in Figure 2 and Table 1.

It is tantalizing that $X(3872)$ lies almost precisely at the $D^0\bar{D}^{*0}$ threshold, 3871.5 MeV. Belle places an upper limit of 2.3 MeV on the width of X. The production rates in 2-TeV $\bar{p}p$ collisions and the similar production characteristics of X and $\psi(2\mathrm{S})$ argue for appreciable prompt production at the Tevatron. A quantitative measure of prompt production *versus* B decay as the source of X should be forthcoming soon.

The natural prejudice is that $X(3872)$ should be identified as the $^3\mathrm{D}_2$ ψ_2 charmonium state, with $J^{PC} = 2^{--}$, but this expectation encounters challenges: The mass is somewhat higher than the 3815 MeV we expected in a single-channel potential model [10], but the mismatch is diminished once we take account of coupling to open-charm channels [11]. Perhaps more serious is the fact that the prominent—even dominant—radiative decays, $\psi_2 \to \gamma\chi_{c1,2}$ that we anticipated have not been seen. At 90% CL, Belle [19,23] limits

$$\mathcal{R}_{1,2} \equiv \frac{\Gamma(X(3872) \to \gamma\chi_{c1,2})}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} < 0.89, 1.1\ . \quad (1)$$

The numerator is readily calculable in the framework of nonrelativistic quantum mechan-

[1] We estimate $\Gamma(h_c \to \gamma\eta_c) \approx 460$ keV in the Cornell coupled-channel model [11], which suggests that $\mathcal{B}(h_c \to \gamma\eta_c) \approx \frac{2}{5}$.

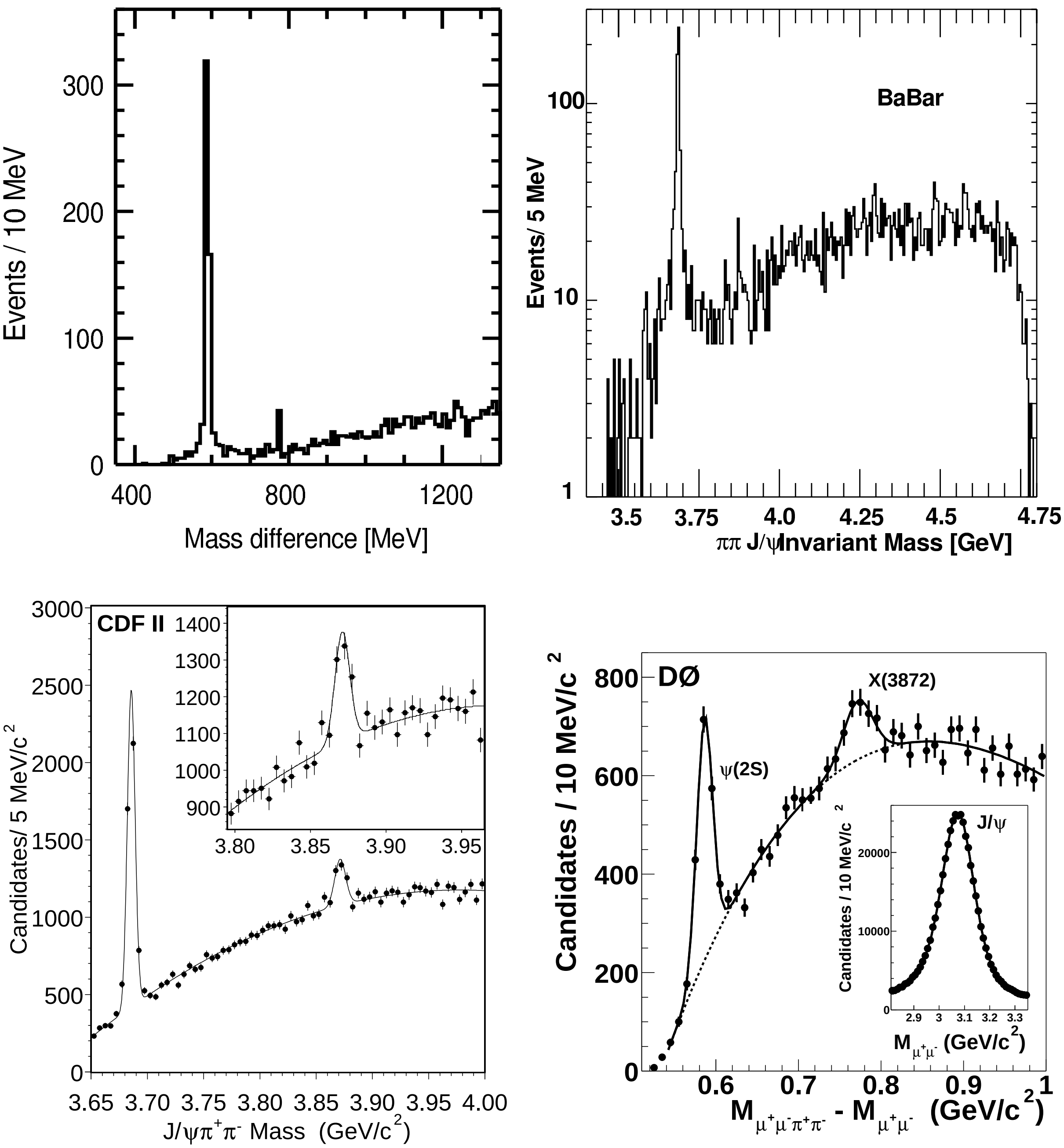

Figure 2. Evidence for $X(3872) \to \pi^+\pi^- J/\psi$, from Belle [19] (top left), BaBar [22] (top right), CDF [20] (bottom left), and DØ [21]. (bottom right). The prominent peak on the left of each panel is $\psi'(3686)$; the smaller peak near $\Delta M \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) \approx 775$ MeV, $M(J/\psi\,\pi^+\pi^-) \approx 3.87$ GeV is $X(3872)$. The CDF and DØ samples are restricted to dipion masses > 500 and 520 MeV, respectively.

Table 1
Observations of $X(3872) \to \pi^+\pi^- J/\psi$. The Belle and BaBar data suggest that high dipion masses are favored; CDF and DØ impose cuts of $M_{\pi\pi} > (500, 520)$ MeV, respectively.

Experiment	Sample	Events	Mass (MeV)
Belle	152M $\Upsilon(4S) \to B\bar{B}$	35.7 ± 6.8	3872.0 ± 0.8
CDF	220 pb^{-1}	730 ± 90	3871.4 ± 0.8
DØ	230 pb^{-1}	522 ± 100	3871.8 ± 4.3
BaBar	117M $\Upsilon(4S) \to B\bar{B}$	25.4 ± 8.7	3873.4 ± 1.4
	Average		3871.9 ± 0.6

ics, but we do not have good theoretical control of the denominator. In the color-multipole expansion, the Wigner-Eckart theorem for E1-E1 transitions predicts equal rates for all the $1\text{D} \to 1\text{S}\,\pi\pi$ cascades, but this does not take into account kinematic differences that arise when the initial 1D states or the final 1S states are not degenerate in mass. Moreover, the one rate to which we might normalize is imperfectly known. The BES-II Collaboration reports $\mathcal{B}(1^3\text{D}_1 \to \pi^+\pi^- J/\psi) = (0.338 \pm 0.137 \pm 0.082)\%$, or $\Gamma(1^3\text{D}_1 \to \pi^+\pi^- J/\psi) = 80 \pm 32 \pm 21$ keV [24]. This value is challenged by a CLEO-c limit [1], $\mathcal{B}(1^3\text{D}_1 \to \pi^+\pi^- J/\psi) < 0.26\%$ at 90% CL. [See Ref. [25] for a critical assessment.] This is a terribly hard measurement, but a precise calibration for the 1D properties is urgently needed!

If, for illustration, we normalize to the BES-II central value, we expect $\mathcal{R}_{1,2} \approx 2.6, 0.6$; the limit (1) on the $\gamma\chi_{c1}$ transition is a source of discomfort for the 1^3D_2 interpretation.

1.4. Alternative Assignments for $X(3872)$

Interpretations of $X(3872)$ other than 1^3D_2 $c\bar{c}$ fall into two classes: those that attribute special significance to the position of X at the $D^0\bar{D}^{*0}$ threshold, and those that treat the threshold as a complicating feature.

The most general threshold remark is that cusps—which may result in narrow resonances—are commonplace when new channels open; a $D\bar{D}^*$ s-wave disturbance would place $X(3872)$ as a 1^{++} state [26]. The notion that charm molecules might be formed by attractive pion exchange between D and $\bar{D}^*$ mesons has a long history, and has been invoked as a possible interpretation for $X(3872)$ by Törnqvist [27] and others [28,29,30]. A maximally attractive channel analysis suggests that lightly bound deuteron analogues, should be $J^{PC} = 0^{-+}$ or 1^{++} states. Symmetries forbid the decay of these levels into $(\pi\pi)_{I=0}J/\psi$; the isospin-violating $(\pi\pi)_{I=1}J/\psi$ mode is required. (The D^+-D^0 and D^{*+}-D^{*0} mass splitting means that the molecule is not a pure isoscalar state.) Although an isovector dipion might account for the observed preference for high dipion masses, it remains to be seen whether the decay rate is large enough. Törnqvist has suggested that the dissociation $X(3872) \to (D^0\bar{D}^{*0})_{\text{virtual}} \to D^0\bar{D}^0\pi^0$ should be a prominent decay mode of a charm molecule, with a partial width of perhaps 50 keV. Belle's limit [31], $\mathcal{B}(B^+ \to K^+X \to K^+\,D^0\bar{D}^0\pi^0) < 6 \times 10^{-5}$, is perhaps an order of magnitude from challenging this expectation. Swanson has suggested other diagnostic decays for charm molecules [32].

What if the $D^0\bar{D}^{*0}$ threshold is not the decisive element? Hybrid states such as $c\bar{c}g$ that manifest the gluonic degrees of freedom might also appear in the charmonium spectrum, and should be examined as interpretations of $X(3872)$ [33].[2] It is fair to say that dynamical calculations of hybrid-meson properties are in a primitive state, but lattice QCD offers some guidance. Liao & Manke find that the lightest hybrids should be 0^{+-}(4.7 GeV), 1^{-+}(4.3 GeV), 2^{+-}(4.9 GeV) [35]. The valence gluon in the hybrid wave function leads to the speculation that the $\eta J/\psi$ mode might be quite prominent. The Babar experiment [36] has found no sign of $X \to \eta J/\psi$ and quoted a limit, $\mathcal{B}(X(3872) \to \eta J/\psi) < 2\mathcal{B}(\psi' \to \eta J/\psi)$, that does not favor a

[2] For the production of hybrid states in B decays, see [34].

privileged role for the $\eta J/\psi$ mode.

A less exotic possibility is that $X(3872)$ should be identified as a charmonium level other than $1^3\mathrm{D}_2$. The $2^1\mathrm{P}_1$ level has been suggested as an alternative assignment for $X(3872)$ because it has an allowed $\pi\pi$ transition to J/ψ and a hindered M1 radiative transition to the 1P levels [37]. The natural-parity $1^3\mathrm{D}_3$ state can decay into $D\bar{D}$, but its f-wave decay is suppressed by the centrifugal barrier factor, so it might be narrow enough to be identified as $X(3872)$. We will examine both of these possibilities in §2.2.

1.5. Additional Experimental Constraints

Where has X production *not* been seen? An analysis of BES data on the radiative return from e^+e^- collisions at $\sqrt{s} = 4.03$ GeV limits $\Gamma(X \to \ell^+\ell^-)\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 10$ eV at 90% CL [38]. A slightly stronger bound follow from from 15 fb^{-1} of CLEO III data: $\Gamma(X \to \ell^+\ell^-)\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 6.8$ eV at 90% CL, which implies $\Gamma(X \to \ell^+\ell^-) < 0.35$ keV for $\mathcal{B}(X \to \pi^+\pi^- J/\psi) > 2\%$ [2]. These bounds make the (already implausible) $3^3\mathrm{S}_1$ charmonium assignment unlikely, and does not encourage any kind of 1^{--} identification.

CLEO III also has examined untagged $\gamma\gamma$ fusion, which might be expected to excite $0^{++}, 0^{-+}, 2^{++}, 2^{-+}, \ldots$ The absence of a signal allows them to set the limit $(2J+1)\Gamma(X \to \gamma\gamma)\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 16.7$ eV at 90% CL [2]. Interpreted as charmonium, none of these states, is expected to show a significant $\pi\pi J/\psi$ decay. The dominant hadronic cascades should instead be $0^{-+} \to \pi\pi\eta_c$, $2^3\mathrm{P}_0 \to \pi\pi 1^3\mathrm{P}_0$ or $3\pi J/\psi$, $2^3\mathrm{P}_2 \to \pi\pi 1^3\mathrm{P}_2$ or $3\pi J/\psi$, $1^1\mathrm{D}_2 \to \pi\pi\eta_c$.

Belle's discovery paper [19] compares the rates of X and ψ' production in B decays,

$$\frac{\mathcal{B}(B^+ \to K^+ X \to K^+\pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \to K^+\psi' \to K^+\pi^+\pi^- J/\psi)} = 0.063 \pm 0.014. \quad (2)$$

Belle [23] presented the first information about the decay angular distribution of J/ψ produced in $X \to \pi^+\pi^- J/\psi$. It does not yet determine J^{PC}, but the 1^{+-} $2^1\mathrm{P}_1$ h_c' assignment is ruled out.[3]

[3]For more on the diagnostic capabilities of decay angular distributions, see Jackson's Les Houches lectures [39] and the recent paper on $X(3872)$ by Pakvasa and Suzuki [37].

2. CHARMONIUM & OPEN CHARM

Stimulated by Belle's discovery of η_c', my colleagues Estia Eichten, Ken Lane, and I outlined a coherent strategy to observe η_c' and the remaining charmonium states that do not decay into open charm, $h_c(1^1\mathrm{P}_1)$, $\eta_{c2}(1^1\mathrm{D}_2)$, and $\psi_2(1^3\mathrm{D}_2)$, through B-meson gateways [10]. We argued that radiative transitions among charmonium levels and $\pi\pi$ cascades to lower-lying charmonia would enable the identification of these states. Ko, Lee and Song [40] discussed the observation of the narrow 1D states by photonic and pionic transitions, and Suzuki [8] emphasized that the cascade decay $B \to h_c K^{(*)} \to \gamma\eta_c K^{(*)}$ offers a promising technique to look for h_c. The position of $X(3872)$ prompted us to analyze the influence of open charm on the properties of charmonium levels that populate the threshold region between $2M_D$ and $2M_{D^*}$ [11].

2.1. A Coupled-Channel Model

Our command of quantum chromodynamics does not yet enable us to derive a realistic description of the interactions that communicate between the $c\bar{c}$ and $c\bar{q} + \bar{c}q$ sectors. The Cornell group showed long ago that a very simple model that couples charmonium to charmed-meson decay channels confirms the adequacy of the single-channel $c\bar{c}$ analysis below threshold and gives a qualitative understanding of the structures observed above threshold [41,42].

The Cornell formalism generalizes the $c\bar{c}$ model without introducing new parameters, writing the interaction Hamiltonian in second-quantized form as

$$\mathcal{H}_I = \tfrac{3}{8}\sum_{a=1}^{8}\int :\rho_a(\mathbf{r})V(\mathbf{r}-\mathbf{r}')\rho_a(\mathbf{r}'): d^3r\, d^3r', \quad (3)$$

where V is the charmonium potential and $\rho_a(\mathbf{r}) = \frac{1}{2}\psi^\dagger(\mathbf{r})\lambda_a\psi(\mathbf{r})$ is the color current density, with ψ the quark field operator and λ_a the octet of SU(3) matrices. To generate the relevant interactions, ψ is expanded in creation and annihilation operators (for charm, up, down, and strange quarks), but transitions from two mesons to three mesons and all transitions that violate the Zweig rule are omitted. It is a good approximation to neglect all effects of the Coulomb piece of the potential in (3).

Table 2
Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially unsplit multiplet.

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
$1^1\mathrm{S}_0$	2 979.9	3 067.6	−90.5	+2.8
$1^3\mathrm{S}_1$	3 096.9		+30.2	−0.9
$1^3\mathrm{P}_0$	3 415.3	3 525.3	−114.9	+5.9
$1^3\mathrm{P}_1$	3 510.5		−11.6	−2.0
$1^1\mathrm{P}_1$	3 525.3		+1.5	+0.5
$1^3\mathrm{P}_2$	3 556.2		−31.9	−0.3
$2^1\mathrm{S}_0$	3 637.7	3 673.9	−50.4	+15.7
$2^3\mathrm{S}_1$	3 686.0		+16.8	−5.2
$1^3\mathrm{D}_1$	3 769.9	(3 815)	−40	−39.9
$1^3\mathrm{D}_2$	3 830.6		0	−2.7
$1^1\mathrm{D}_2$	3 838.0		0	+4.2
$1^3\mathrm{D}_3$	3 868.3		+20	+19.0
$2^3\mathrm{P}_0$	3 931.9	3 968	−90	+10
$2^3\mathrm{P}_1$	4 007.5		−8	+28.4
$2^1\mathrm{P}_1$	3 968.0		0	−11.9
$2^3\mathrm{P}_2$	3 966.5		+25	−33.1

The basic coupled-channel interaction (3) is spin-independent, but the different energy denominators induce spin-dependent forces that affect the charmonium states. These spin-dependent forces give rise to S-D mixing that contributes to the $\psi(3770)$ electronic width, for example, and are a source of additional spin splitting, shown in the rightmost column of Table 2. To compute the induced splittings, we adjust the bare centroid of the spin-triplet states so that the physical centroid, after inclusion of coupled-channel effects, matches the value in the middle column of Table 2. As expected, the shifts induced in the low-lying 1S and 1P levels are small. For the other known states in the 2S and 1D families, coupled-channel effects are noticeable and interesting.

In a simple potential picture, the $\eta_c'(2^1\mathrm{S}_0)$ level lies below the $\psi'(2^3\mathrm{S}_1)$ by the hyperfine splitting given by $M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$. Normalizing to the observed 1S hyperfine splitting, $M(J/\psi) - M(\eta_c) = 117$ MeV, we would find $M(\psi') - M(\eta_c') = 67$ MeV, which is larger than the observed 48.3 ± 4.4 MeV, as is typical for potential-model calculations. The 2S induced shifts in Table 2 draw ψ' and η_c' closer by 20.9 MeV, substantially improving the agreement between theory and experiment. It is tempting to conclude that the ψ'-η_c' splitting reflects the influence of virtual decay channels.

We peg the 1D masses to the observed mass of the $1^3\mathrm{D}_1$ $\psi(3770)$. In our model calculation, the coupling to open-charm channels increases the $1^3\mathrm{D}_2$-$1^3\mathrm{D}_1$ splitting to about 60 MeV, but does not fully account for the observed 102 MeV separation between $X(3872)$ and $\psi(3770)$. Is it significant that the position of the 3^{--} $1^3\mathrm{D}_3$ level turns out to be very close to 3872 MeV? For the 2P levels, we have no experimental anchor, so we adjust the bare centroid so that the $2^1\mathrm{P}_1$ level lies at the centroid of the potential-model calculation.

The physical charmonium states are not pure

Table 3
Calculated rates for E1 radiative decays of some 1D levels. *Values in italics* result if the influence of open-charm channels is not included.

Transition (γ energy in MeV)	Partial width (keV)
$1^3\mathrm{D}_2(3872) \to \chi_{c2}\,\gamma(303)$	*85* $\to$ 45
$1^3\mathrm{D}_2(3872) \to \chi_{c1}\,\gamma(344)$	*362* $\to$ 207
$1^3\mathrm{D}_3(3872) \to \chi_{c2}\,\gamma(304)$	*341* $\to$ 299

potential-model eigenstates. To compute the E1 radiative transition rates, we must take into account both the standard $(c\bar{c}) \to (c\bar{c})\gamma$ transitions and the transitions between (virtual) decay channels in the initial and final states. Our expectations for E1 decays of the $1^3\mathrm{D}_2$ and $1^3\mathrm{D}_3$ candidates for $X(3872)$ are shown in Table 3.

2.2. Decays into Open Charm

Once the position of a resonance is given, the coupled-channel formalism yields reasonable predictions for the other resonance properties. The $1^3\mathrm{D}_1$ state $\psi''(3770)$, which lies some 40 MeV above charm threshold, offers an important benchmark: we compute $\Gamma(\psi''(3770) \to D\bar{D}) = 20.1$ MeV, to be compared with the Particle Data Group's fitted value of 23.6 ± 2.7 MeV [18]. The variation of the $1^3\mathrm{D}_1$ width with mass is shown in the top left panel of Figure 3.[4]

The long-standing expectation that the $1^3\mathrm{D}_2$ and $1^1\mathrm{D}_2$ levels would be narrow followed from the presumption that these unnatural parity states should lie between the $D\bar{D}$ and $D\bar{D}^*$ thresholds, and could not decay into open charm. At 3872 MeV, both states can decay into $D^0\bar{D}^{*0}$, but the partial widths are quite small. We show the variation of the $1^3\mathrm{D}_2$ partial width with mass in the top right panel of Figure 3; over the region of interest, it does not threaten the Belle bound, $\Gamma(X(3872)) < 2.3$ MeV. The range of values is quite similar to the range estimated for $\Gamma(1^3\mathrm{D}_2 \to \pi\pi J/\psi)$, so we expect roughly comparable branching fractions for decays into $D^0\bar{D}^{*0}$ and $\pi^+\pi^- J/\psi$. If $X(3872)$ does turn out to be the $1^3\mathrm{D}_2$ level, we expect $M(1^1\mathrm{D}_2) = 3880$ MeV and $\Gamma(1^1\mathrm{D}_2 \to D^0\bar{D}^{*0}) \approx 1.7$ MeV.

The natural-parity $1^3\mathrm{D}_3$ state can decay into $D\bar{D}$, but its f-wave decay is suppressed by the centrifugal barrier factor, so the partial width is less than 1 MeV at a mass of 3872 MeV. Although estimates of the hadronic cascade transitions are uncertain, the numbers in hand lead us to expect $\Gamma(1^3\mathrm{D}_3 \to \pi^+\pi^- J/\psi) \lesssim \frac{1}{4}\Gamma(1^3\mathrm{D}_3 \to D\bar{D})$, whereas $\Gamma(1^3\mathrm{D}_3 \to \gamma\chi_{c2}) \approx \frac{1}{3}\Gamma(1^3\mathrm{D}_3 \to D\bar{D})$, if $X(3872)$ is identified as $1^3\mathrm{D}_3$. The variation of $\Gamma(1^3\mathrm{D}_3 \to D\bar{D})$ with mass is shown in the middle left panel of Figure 3. Note that if $1^3\mathrm{D}_3$ is not to be identified with $X(3872)$, *it may still be discovered as a narrow $D\bar{D}$ resonance,* up to a mass of about 4000 MeV.

In their study of $B^+ \to K^+\psi(3770)$ decays, the Belle Collaboration [31] has set 90% CL upper limits on the transition $B^+ \to K^+X(3872)$, followed by $X(3872) \to D\bar{D}$. Their limits imply that $\mathcal{B}(X(3872) \to D^0\bar{D}^0) \lesssim 4\mathcal{B}(X \to \pi^+\pi^- J/\psi)$, and $\mathcal{B}(X(3872) \to D^+D^-) \lesssim 3\mathcal{B}(X \to \pi^+\pi^- J/\psi)$. This constraint is already intriguingly close to the level at which we would expect to see $1^3\mathrm{D}_3 \to D\bar{D}$.

The constraint on the total width of $X(3872)$ raises more of a challenge for the $2^1\mathrm{P}_1$ candidate, whose s-wave decay to $D^0\bar{D}^{*0}$ rises dramatically from threshold, as shown in the middle right panel of Figure 3. Within the current uncertainty (3871.7 ± 0.6 MeV) in the mass of X, the issue cannot be settled, but the $2^1\mathrm{P}_1$ interpretation is viable only if X lies below $D^0\bar{D}^{*0}$ threshold. If a light $2^1\mathrm{P}_1$ does turn out to be $X(3872)$, then its $2^3\mathrm{P}_J$ partners should lie nearby. In that case, they should be visible as relatively narrow charm-anticharm resonances. At 3872 MeV, we estimate $\Gamma(2^3\mathrm{P}_1 \to D\bar{D}^*) \approx 21$ MeV and $\Gamma(2^3\mathrm{P}_2 \to D\bar{D}) \approx 3$ MeV. The bottom left panel

[4] Barnes & Godfrey [43] estimated the decays of several of the charmonium states into open charm, using the $^3\mathrm{P}_0$ model of $q\bar{q}$ production, but without carrying out a coupled-channel analysis.

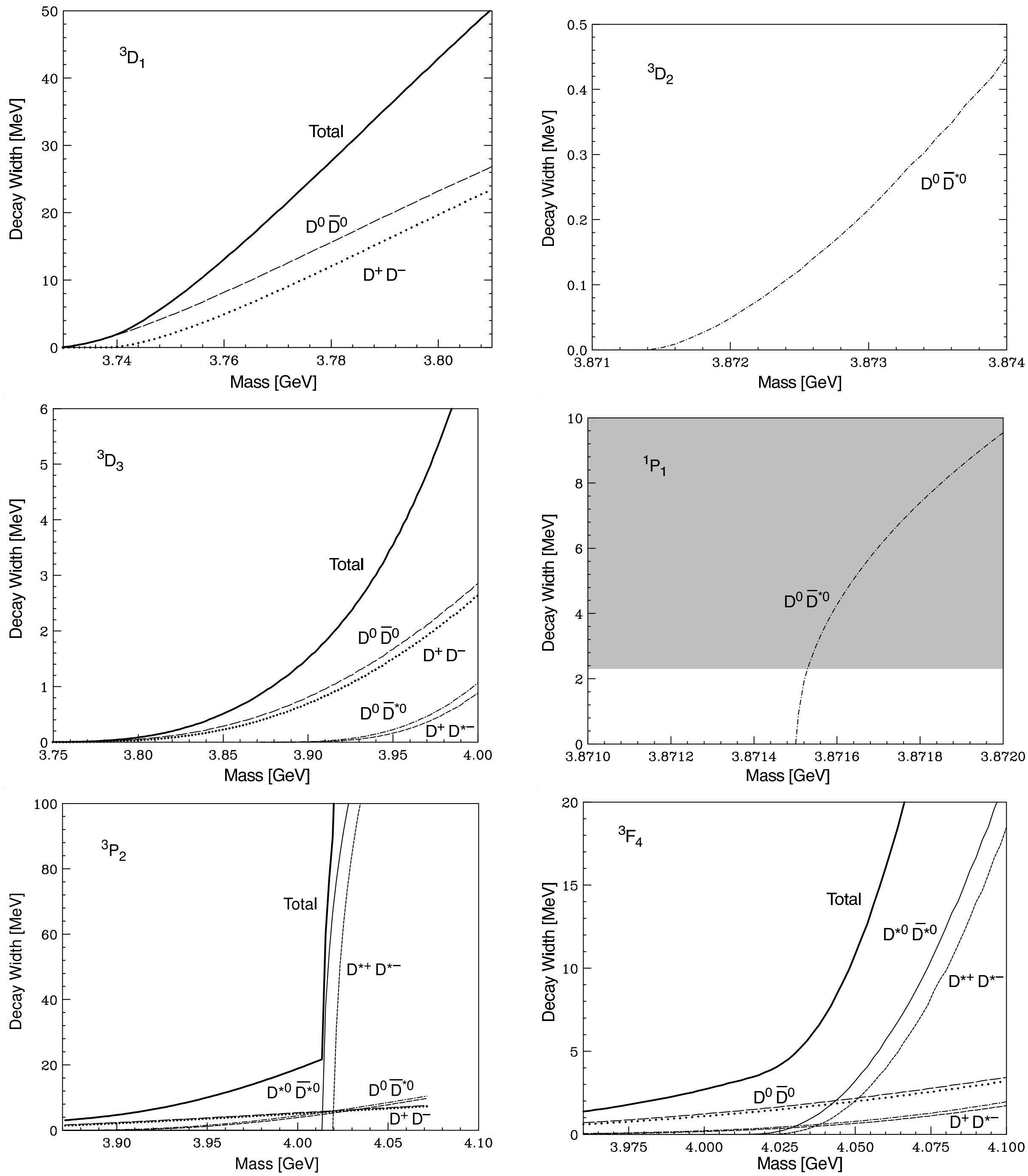

Figure 3. Partial and total widths near threshold for decay of charmonium states into open charm, computed in the Cornell coupled-channel model. Long dashes: $D^0\bar{D}^0$, dots: D^+D^-, dot-dashes: $D^0\bar{D}^{*0}$, dashes: D^+D^{*-}, thin line: $D^{*0}\bar{D}^{*0}$, short dashes: $D^{*+}D^{*-}$, widely spaced dots: $D_s\bar{D}_s$, thick line: sum of open-charm channels. Belle's 90% C.L. upper limit [19], $\Gamma(X(3872)) < 2.3$ MeV, is indicated on the $^1\mathrm{P}_1$ window. For $D\bar{D}^*$ modes, the sum of $D\bar{D}^*$ and $\bar{D}D^*$ is always implied.

in Figure 3 shows that the $2^3\mathrm{P}_2$ level remains relatively narrow up to the opening of the $D^*\bar{D}^*$ threshold.

I point out one more candidate for a narrow resonance of charmed mesons: The $1^3\mathrm{F}_4$ level remains narrow ($\Gamma(1^3\mathrm{F}_4 \to \mathrm{charm}) \lesssim 5$ MeV) up to the $D^*\bar{D}^*$ threshold, as illustrated in the bottom right panel of Figure 3. Its allowed decays into $D\bar{D}$ and $D\bar{D}^*$ are inhibited by $\ell = 4$ barrier factors, whereas the $D^*\bar{D}^*$ channel is reached by $\ell = 2$.

3. FOLLOWING UP $X(3872)$

The first order of experimental business is to establish the nature of $X(3872)$. The charmonium interpretation and its prominent rivals require that $X(3872)$ be a neutral isoscalar. Are there charged partners? In the decay $X(3872) \to \pi^+\pi^- J/\psi$, the dipion angular distributions and the dipion mass spectrum [44] should lead to a better understanding of the X quantum numbers. Determining the J^{PC} quantum numbers of X is absolutely crucial to thin the herd of candidates. Other diagnostics of a general nature have been discussed in Refs. [33,43,37,45].

A search for $X(3872) \to \pi^0\pi^0 J/\psi$ will be highly informative. Observing a significant $\pi^0\pi^0 J/\psi$ signal establishes that X is odd under charge conjugation [43]. The ratio $\mathcal{R}_0 \equiv \Gamma(X \to \pi^0\pi^0 J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi)$ measures the dipion isospin [46]. Writing $\Gamma_I \equiv \Gamma(X \to (\pi^+\pi^-)_I J/\psi)$, we see that $\mathcal{R}_0 = \frac{1}{2}/(1 + \Gamma_1/\Gamma_0)$, up to kinematic corrections. Deviations from $\mathcal{R}_0 = \frac{1}{2}$ signal the isospin-violating decay of an isoscalar, or the isospin-conserving decay of an isovector. Radiative decay rates and the prompt (as opposed to B-decay) production fraction will provide important guidance.

Within the charmonium framework, $X(3872)$ is most naturally interpreted as the $1^3\mathrm{D}_2$ or $1^3\mathrm{D}_3$ level, both of which have allowed decays into $\pi\pi J/\psi$. The 2^{--} $1^3\mathrm{D}_2$ state is forbidden by parity conservation to decay into $D\bar{D}$ but has a modest $D^0\bar{D}^{*0}$ partial width for masses near 3872 MeV. Although the uncertain $\pi\pi J/\psi$ partial width makes it difficult to estimate relative branching ratios, the decay $X(3872) \to \chi_{c1}\,\gamma(344)$ should show itself if X is indeed $1^3\mathrm{D}_2$. The $\chi_{c2}\,\gamma(303)$ line should be seen with about $\frac{1}{4}$ the strength of $\chi_{c1}\,\gamma(344)$. In our coupled-channel calculation, the $1^3\mathrm{D}_2$ mass is about 41 MeV lower than the observed 3872 MeV. In contrast, the computed $1^3\mathrm{D}_3$ mass is quite close to 3872 MeV, and $1^3\mathrm{D}_3$ does not have an E1 transition to $\chi_{c1}\,\gamma(344)$. The dominant decay of the 3^{--} $1^3\mathrm{D}_3$ state should be into $D\bar{D}$; a small branching fraction for the $\pi\pi J/\psi$ discovery mode would imply a large production rate. One radiative transition should be observable, with $\Gamma(X(3872) \to \chi_{c2}\,\gamma(303)) \gtrsim \Gamma(X(3872) \to \pi^+\pi^- J/\psi)$. I stress the importance of searching for the $\chi_{c1}\,\gamma(344)$ and $\chi_{c2}\,\gamma(303)$ lines.

It will not be easy to improve on the existing bound, $\Gamma(X(3872)) < 2.3$ MeV [19], but a tighter limit or, ideally, a measurement, would be a very useful discriminant for theoretical interpretations.

Beyond pinning down the character of $X(3872)$, experiments can search for additional narrow charmonium states in radiative and hadronic transitions to lower-lying $c\bar{c}$ levels, as we emphasized in Ref. [10,11]. To underscore an obvious target: if $X(3872)$ is $1^3\mathrm{D}_3$, then $1^3\mathrm{D}_2$ lies near 3835 MeV. Looking for additional narrow structures in the $\pi^+\pi^- J/\psi$ mass spectrum could be highly rewarding. *You haven't found everything yet!*

The coupled-channel analysis presented in our most recent paper [11] sets up specific targets for narrow structures in neutral combinations of charmed mesons and anticharmed mesons. The most likely candidates correspond to $1^3\mathrm{D}_3$, with $\Gamma(1^3\mathrm{D}_3 \to D\bar{D}) \lesssim 1$ MeV; $1^3\mathrm{F}_4$, with $\Gamma(1^3\mathrm{F}_4 \to D\bar{D}) \lesssim 5$ MeV for $M \lesssim 2M(D^*)$; and $2^3\mathrm{P}_2$, with $\Gamma(2^3\mathrm{P}_2 \to D\bar{D}, D\bar{D}^*) \lesssim 20$ MeV for $M \lesssim 2M(D^*)$.

Finally, let us not neglect the importance to charmonium spectroscopy of establishing the $1^1\mathrm{P}_1$ h_c and confirming the quantum numbers of the $2^1\mathrm{S}_0$ $\eta_c'(3638)$.

Theorists also have plenty to do. We must improve our understanding of the influence of open-charm channels. Because the Cornell coupled-channel model is only an approximation to QCD, it would be highly desirable to compare its predictions with those of a coupled-channel analysis of the $^3\mathrm{P}_0$ model of quark pair production.[5] Ultimately, extending lattice QCD calculations into the flavor-threshold region should give a firmer basis for predictions. The analysis we have carried out [11] can be extended to the $b\bar{b}$ system, where it may be possible to see discrete threshold-region states in direct hadronic production.

We need a more complete understanding of the production of the charmonium states in B decays and by direct hadronic production. We need to improve the theoretical understanding of hadronic cascades among charmonium states, including the influence of open-charm channels. The comparison of charmonium transitions with their upsilon counterparts should be informative.

The outstanding theoretical challenge for the charmed molecule hypothesis is to understand possible production mechanisms of these apparently large and fragile states. The $c\bar{c}g$ hybrid-meson hypothesis needs further development, with specific predictions for the production mechanisms and properties of the states and a decision tree to test the interpretation.

4. OUTLOOK

The discovery of the narrow state $X(3872) \to \pi^+\pi^- J/\psi$ gives charmonium physics a rich and lively puzzle. We do not yet know what this state is. If the most conventional interpretation as a charmonium state—most plausibly, the $1^3\mathrm{D}_2$ or $1^3\mathrm{D}_3$ level—is confirmed, we will learn important lessons about the influence of open-charm states on $c\bar{c}$ levels. Should the charmonium interpretation not prevail, perhaps $X(3872)$ will herald an entirely new spectroscopy. In either event, several new charmonium states remain to be discovered through their radiative decays or hadronic transitions to lower $c\bar{c}$ levels. Another set of $c\bar{c}$ states promise to be observable as narrow structures that decay into pairs of charmed mesons. In time, comparing what we learn from this new exploration of the charmonium spectrum with analogous states in the $b\bar{b}$ and $b\bar{c}$ families will be rewarding. For all three quarkonium families, we need to improve our understanding of hadronic cascades. Beyond spectroscopy, we look forward to new insights about the production of quarkonium states in B decays and hard scattering. The rapid back-and-forth between theory and experiment is great fun, and I look forward to learning many new lessons!

[5] A preliminary mention of work in progress by Barnes, Godfrey, & Swanson appears in Ref. [47].

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